A Program of Long Baseline Neutrino Exploration at Fermilab

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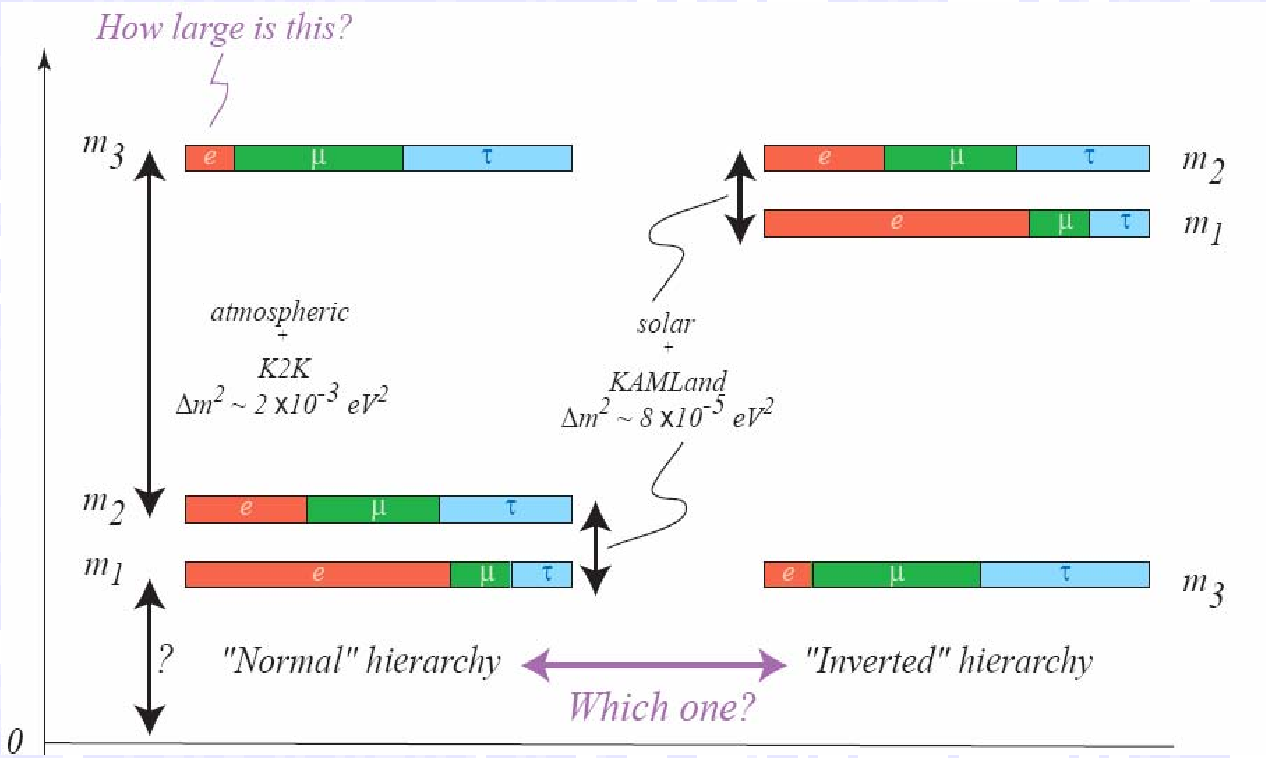
What we know, what we would like to know…



Would like to have more precise knowledge of mixing. Do ν_e's participate in oscillations at atmospheric scale?

Is $\Delta m^2_{23} > 0$ or < 0?

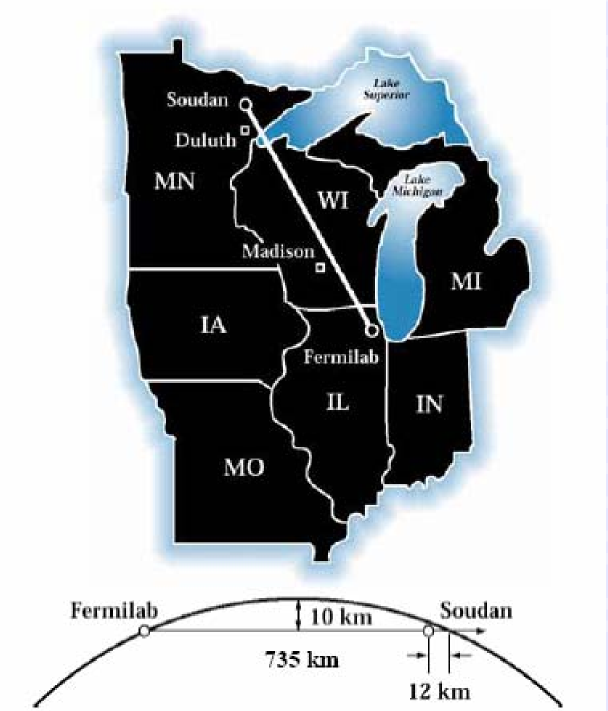
Is CP violated?

The Fermilab long-range plan for long baseline experiments addresses all of these issues in a step-by-step program of detectors and beamline upgrades.

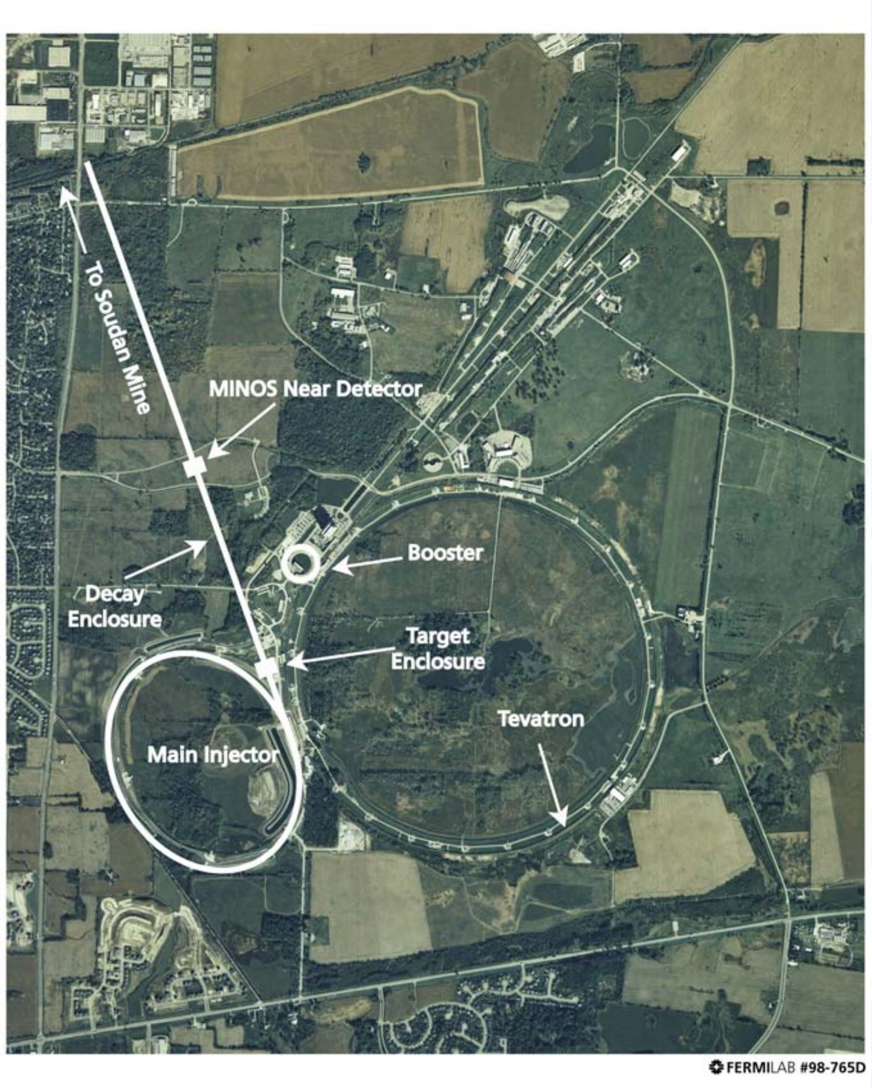
MINOS (Main Injector Neutrino Oscillation Search)

Long baseline oscillation experiment designed to:

- Demonstrate oscillation behavior
  - Confirm and describe flavour oscillations
  - Provide *high statistics* discrimination against alternative models (decoherence, ν decay, extra dimensions, etc.)
- Precise Measurement of Δm^2_{23} to ~ 10%
- Search for $\nu_\mu \to \nu_e$ oscillations (θ_{13})
- First direct measurement of ν vs $\bar{\nu}$ oscillations from atmospheric neutrino events
  - MINOS is the first large deep underground detector with a B-field



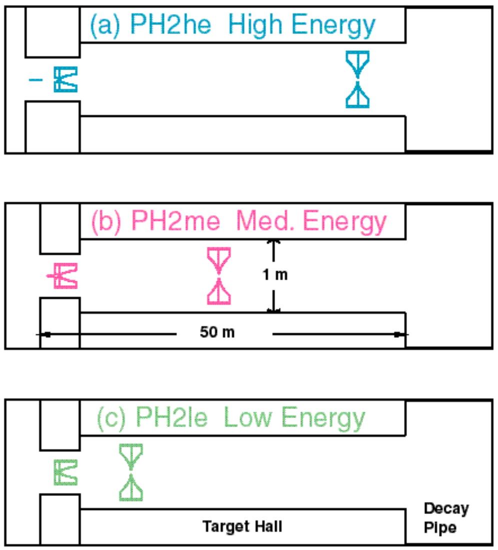
The NuMI beam

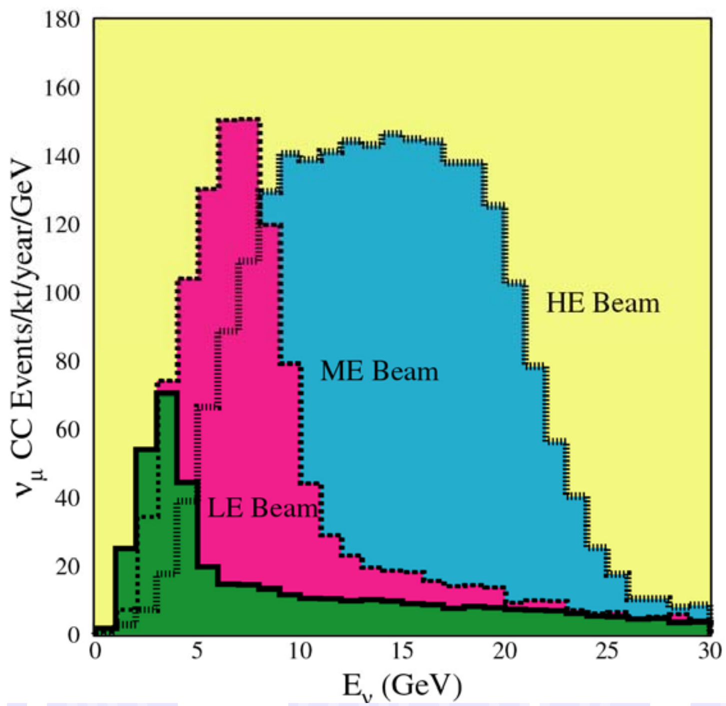


- 120 GeV protons extracted from the Main Injector in a single turn (8.7μs)
- 1.9 s cycle time *i.e.* ν beam \`on' for 8.7 ms every 1.9 s
- 2.5×10^{13} protons/pulse initially
- 2.5×10^{20} protons/year initial intensity
- 0.25 MW on target !
- 0.4 MW at 4×10^{13} p/pulse!

Tuneable Beam

- Relative position of target and horns allows tuning of beam energy. Act like a pair of highly achromatic lenses.
- MINOS starts with LE beam - best for $\Delta m^2 \sim 0.002\ eV^2$
- Can run neutrinos or antineutrinos





LE BEAM:

ν_μ **CC Events Observed / yr:**

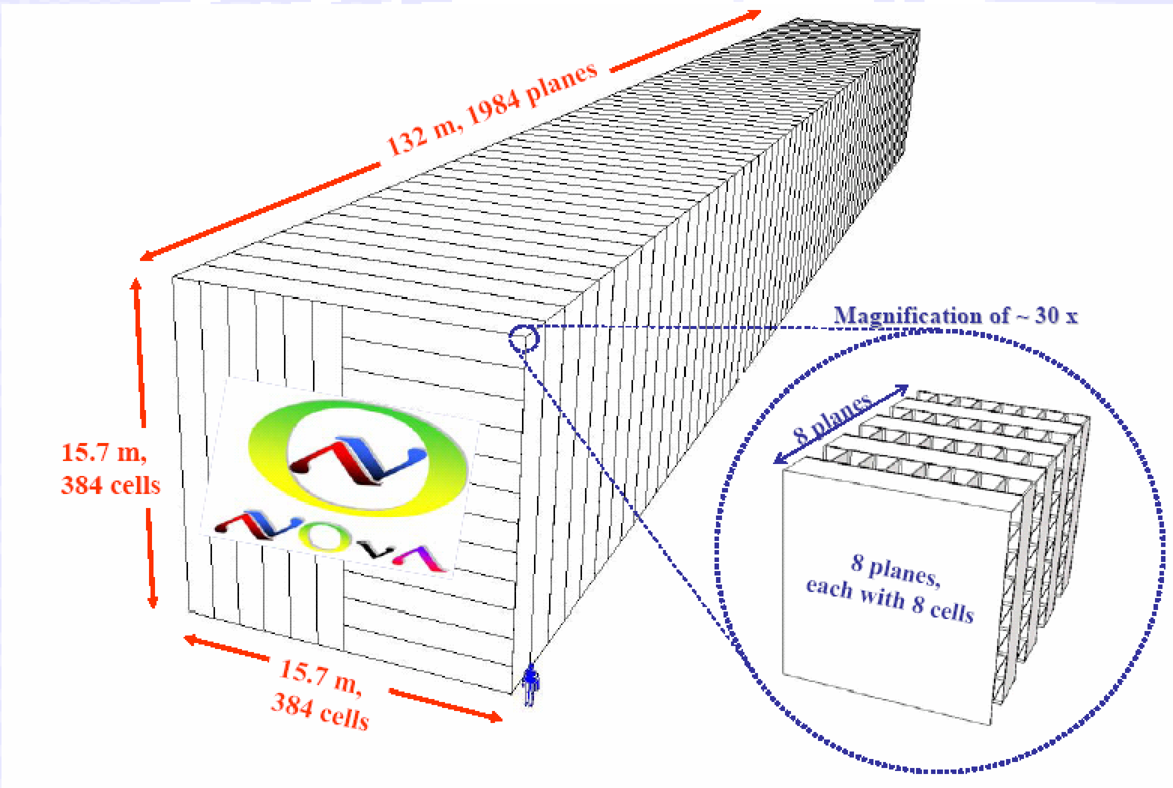
Low	Medium	High
1600	4300	9250

(2.5×10^{20} protons on target / year)

NOνA

NuMI Off-Axis ν_e Appearance Experiment

Argonne, Athens, Caltech, UCLA, Fermilab, College de France, Harvard, Indiana, ITEP, Lebedev, Michigan State, Minnesota/Duluth, Minnesota/Minneapolis, Munich, Stony Brook, Northern Illinois, Ohio, Ohio State, Oxford, Rio de Janeiro, Rutherford, South Carolina, Stanford, Texas A&M, Texas/Austin, Tufts, Virginia, Washington, William & Mary, Wisconsin



Goals of the NOνA Experiment

- Observe ν_e appearance
- Sensitivity to $\sin^2(2\theta_{13})$ a factor of 10 below CHOOZ sensitivity, i.e. down to ~ 0.01
- $\sin^2(2\theta_{23})$ measurement to 2% accuracy
- Resolve or contribute to determination of mass hierarchy via matter effects
- Begin to study CP violation in lepton sector

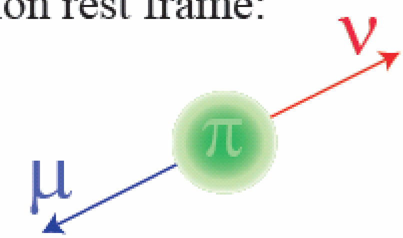
How NOνA Will Meet its Goals

- Reduce backgrounds to ν_e appearance search by going off the NUMI beam axis for a narrow-band beam. Will use Medium Energy configuration.
- Increase flux/POT at oscillation max by ~2 by going off-axis
- Increase detector mass a factor of 6 over MINOS while reducing cost/kiloton by a factor of 3
- 80% active detector design (compared to 1.5 X_0 sampling in MINOS)
  - electron showers appear as “fuzzy” tracks with 1-4 hits/plane/view
  - allow better separation of γ's from π^0 decays
  - good energy resolution to focus on signal energy region
- Choose long baseline to enhance matter effects

Off-Axis Neutrino Beams

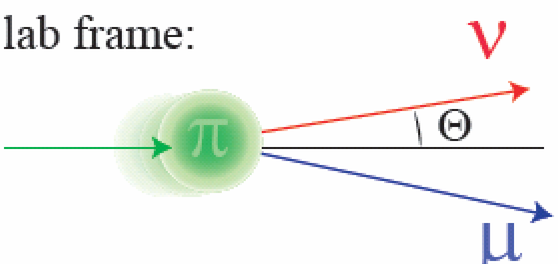
First proposed by BNL E-889

In pion rest frame:

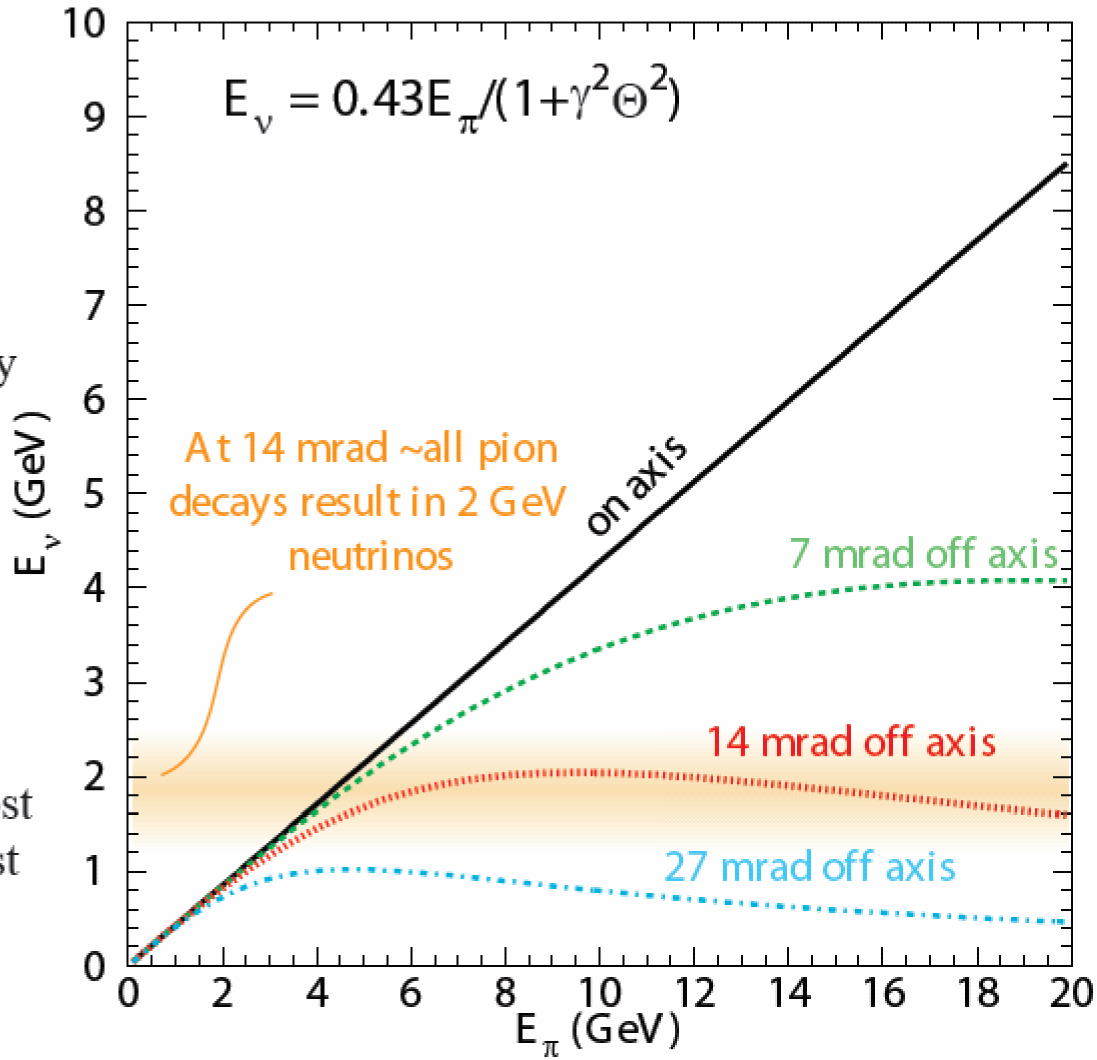


Neutrino and muon energy completely determined by energy conservation

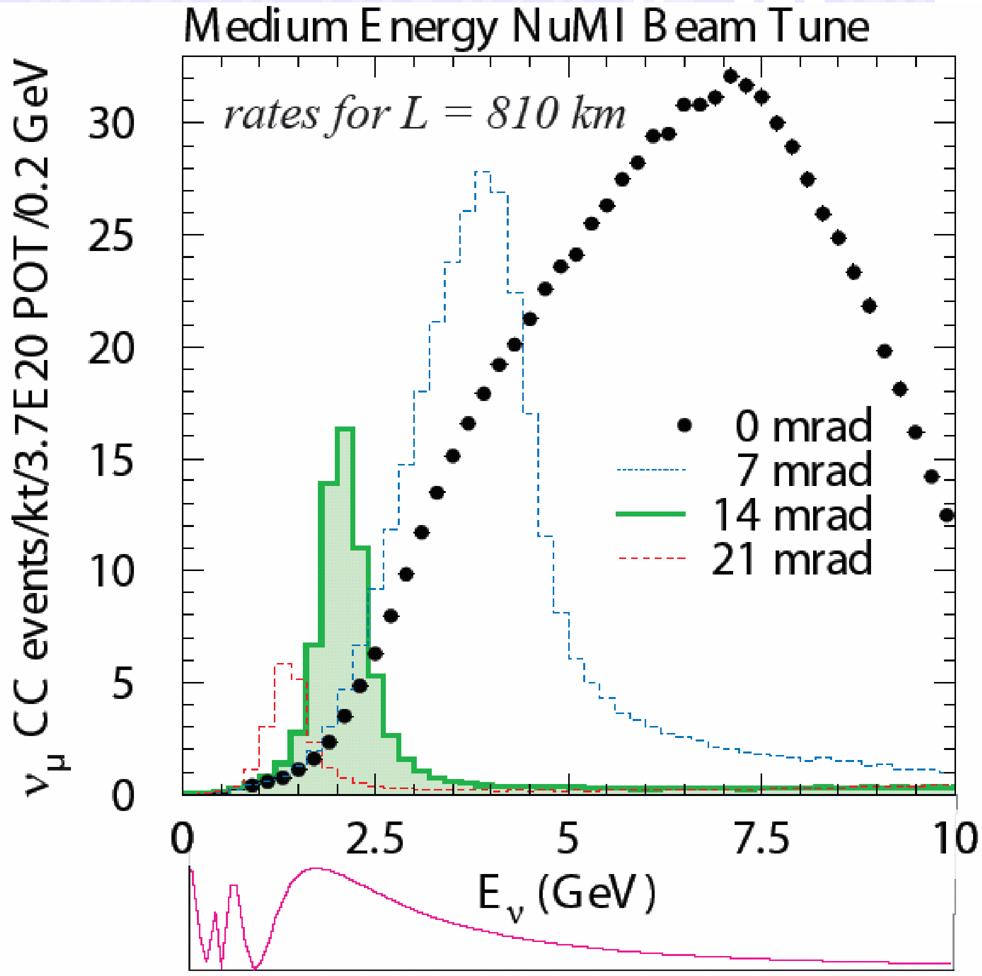
In lab frame:



Neutrino energy depends on boost and angle between neutrino boost direction



NUMI Neutrino Spectra



- 14 mrad off-axis beam peaks just above oscillation max at ~ 2 GeV with ~20% width
- High energy tail suppressed
  - Reduces NC and τ backgrounds
- Main peak from π decays. K decay ν at much wider angles.
  - Spectrum prediction insensitive to knowledge of k/π ratio

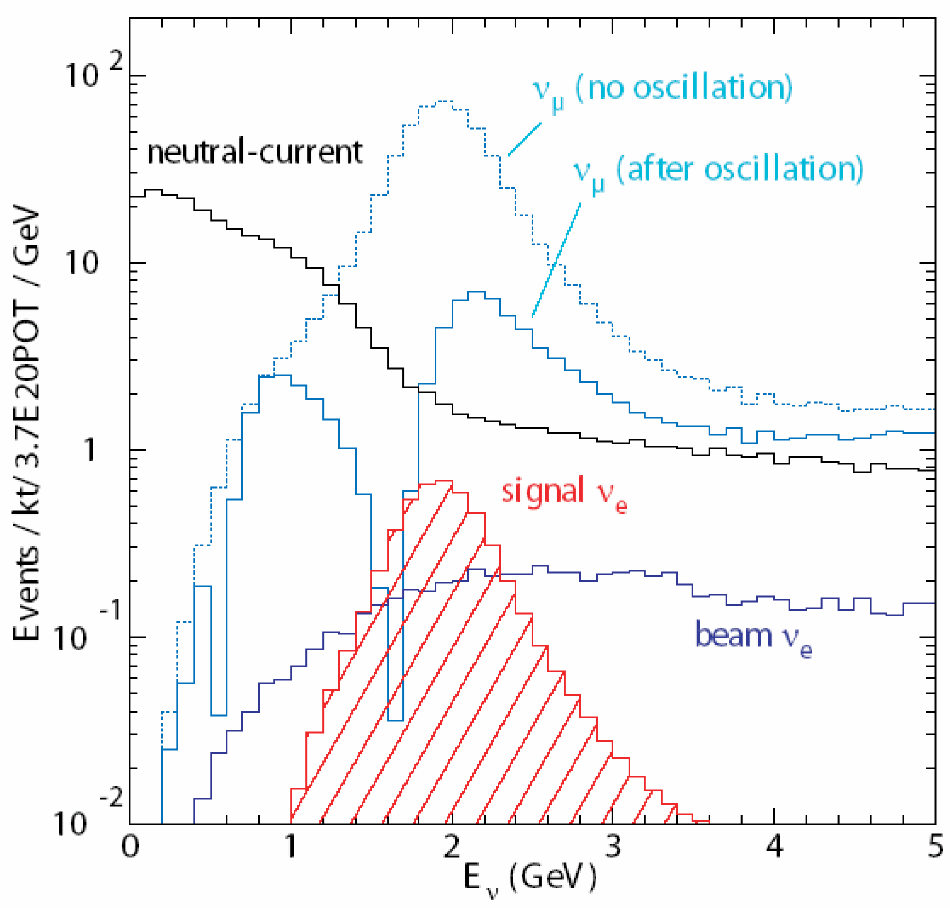
Event Rates

Event rates calculated for

- L=810 km, 12 km off-axis
- $\Delta m^2_{23} = 2.5 \times 10^{-3}\ eV^2$
- $Sin^2 2\theta_{23} = 1$
- $Sin^2 2\theta_{13} = 0.01$

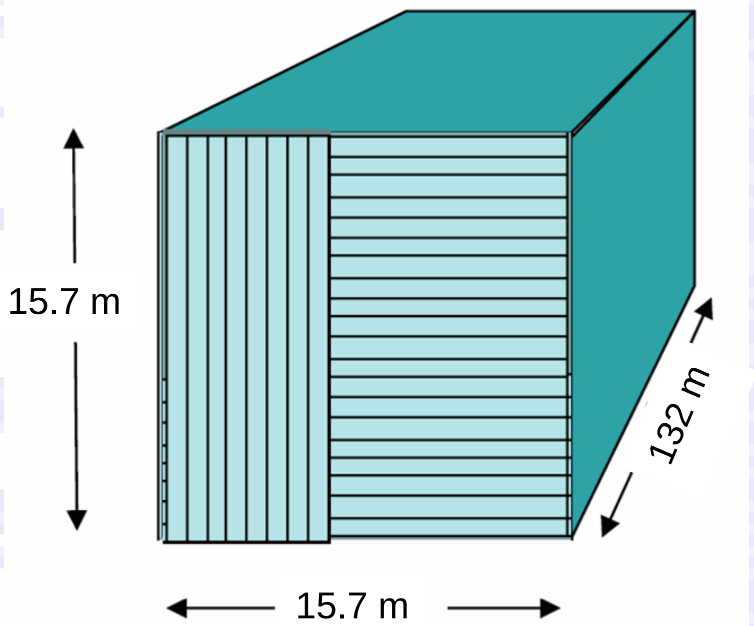
To Reject Background:

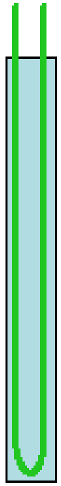
- 50:1 rejection of ν_μ CC required
  ⇨ Easy!
- Need 100:1 NC rejection
  ⇨ fine grained, low density
- Good energy resolution
  ⇨ reject beam ν_e



The NOνA Far Detector

- 30 kT, low Z tracking calorimeter
- 80% active material (by weight).
- Optimized for detecting 2 GeV electrons.
- PVC extrusions filled with Liq. Scint.
  - Cell size of 3.87cm x 6.0 cm x 15.7 m
  - 12 extrusions/plane
  - 32 cells/extrusion
  - 1984 planes
  - = 23,808 extrusions
  - = 761,856 channels
- 0.8 mm looped WLS fiber into APD readout

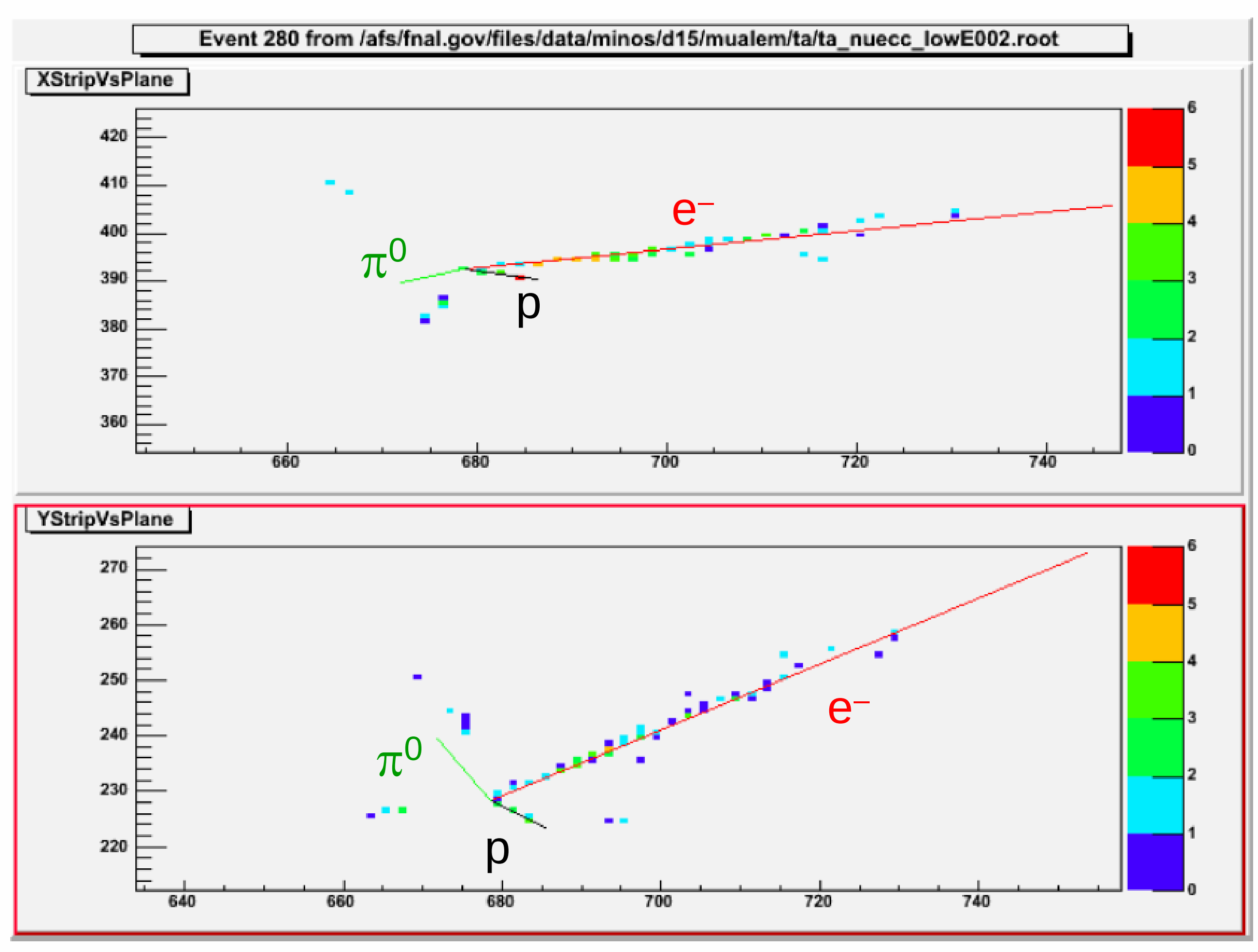




APD Readout

- Cooled to -15° C
- Q.E. 85%
- 22 p.e. at far end
- 250 e noise
- S/N 10:1

Typical NOνA Event: $\nu_e A \rightarrow p\, e^- \pi^0$, E_ν = 1.65 GeV



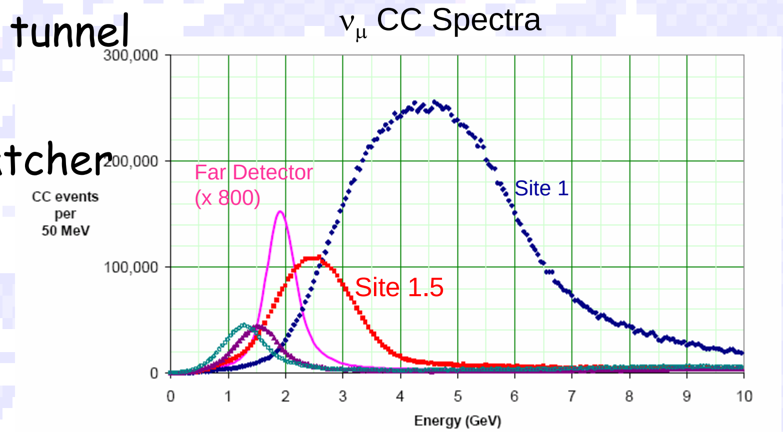
Signal efficiency 24%

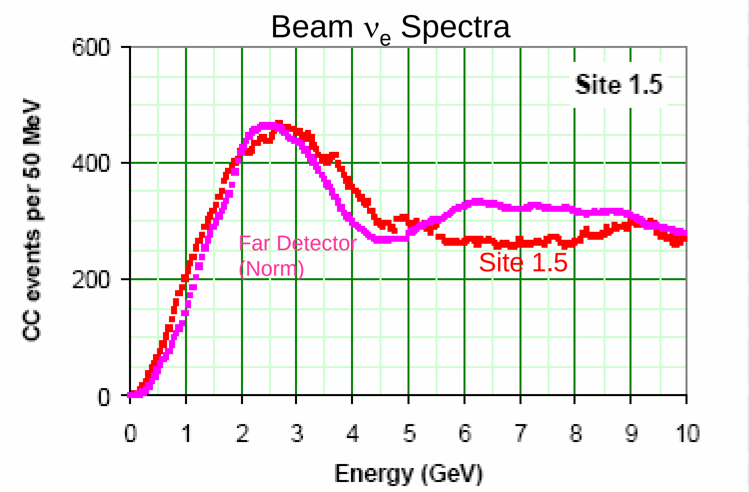
signal/background 7.3

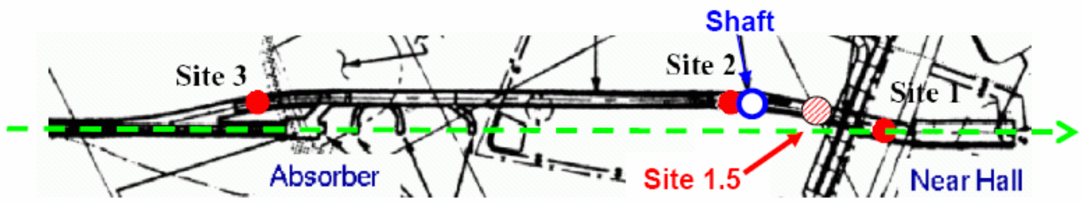
signal/sqrt(bg.) 32

NOνA Near Detector

- ~ 1 km from NUMI target
- Fits in several existing locations in NUMI access tunnel
  - 3.5 m x 4.8 m x 9.6 m
  - Includes veto, shower containment, muon catcher
- No single location optimizes all parameters
  - Make movable or build more than 1







NOνA Milestones

Milestone	Date (in months relative to Project Start)	Proposed Calendar Date	FY
Project Start	t_0	October, 2006	07
Order extrusions and fiber	t_0+1	Nov., 2007	07
Start extrusion module factories	t_0+12	October, 2007	08
Start operation of Near Detector	t_0+21	July, 2008	08
Far building complete	t_0+31	May, 2009	09
Start Construction of Far detector	t_0+31	May, 2009	09
First kiloton operational	t_0+36	Oct., 2009	10
First 15 kilotons operational	t_0+47	June 2010	10
Full 30 kilotons operational	t_0+57	July, 2011	11

Fermilab Proton Plan

	Booster Batch Size	Main Injector Load	Cycle Time	MI Intensity	Booster Rate*	Total Proton Rate	Annual Rate at end of Phase	
		(AP + NuMI)	(sec)	(protons)	(Hz)	(p/hr)	**NuMI**	**BNB**
Actual Operation								
July, 04	5.0E+12	1+0	2.0	0.5E+13	5.1	0.8E+17	0	3.3E+20
Proton Plan								
Phase I	5.10E+12	2+1→2+5	2.0	3.6E+13	6.3	1.0E+17	2.0E+20	1.5E+20
Phase II	5.3E+12	2+5	2.0	3.7E+13	7.5	1.2E+17	2.2E+20	2.8E+20
Phase III	5.50E+12	2+9	2.2	6.0E+13	8.3	1.5E+17	3.4E+20	2.2E+20
Beyond Scope of Present Plan								
11 Hz	5.50E+12	2+9	2.2	6.1E+13	11.0	2.0E+17	3.4E+20	5.0E+20

2008

TABLE 6: Performance parameters at the completion of each phase of operation.
* Booster rate is limited by radiation levels, except for the 11 Hz case

http://www.fnal.gov/directorate/program_planning/Nov2004PACPublic/Draft_Proton_Plan_v2.pdf

Fermilab Proton Plan after 2009

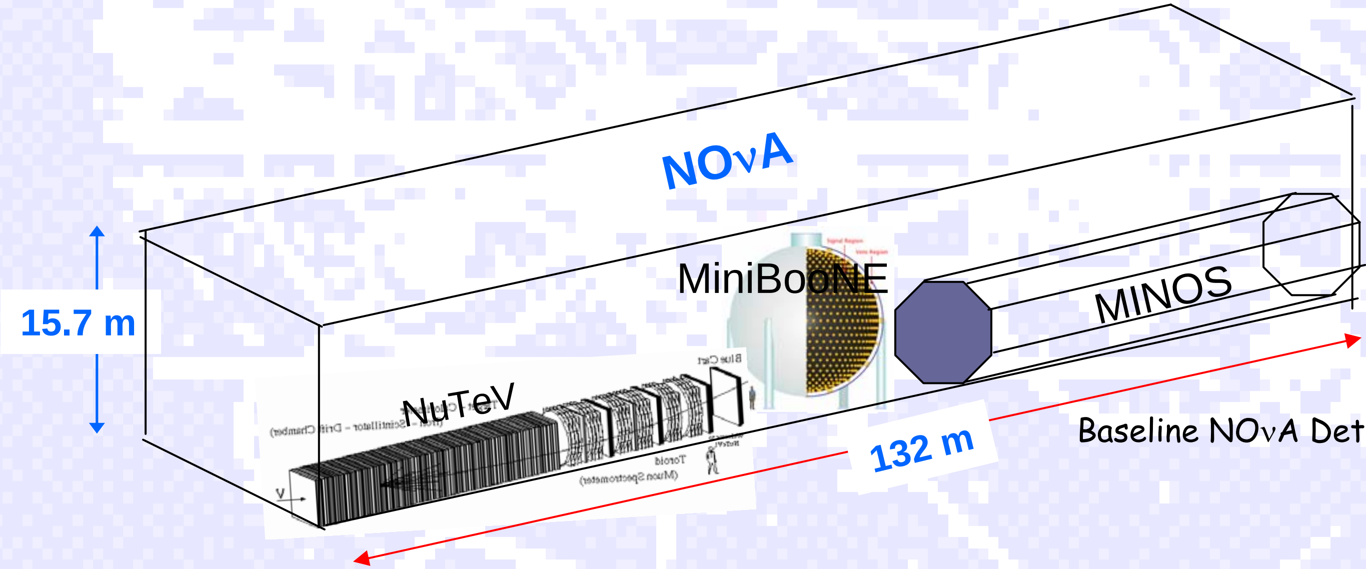
Collider operations end in 2009

- Proton bunches in MI used to $\bar{p}$ now available to NuMI → × 11/9
- No NuMI downtime due to shot setup (10%) or antiproton transfers to Recycler (5%) → × 1.176
- Load 11 booster batches into Recycler and transfer from Recycler to MI in a single booster cycle. MI cycle time reduced from 2.2 s to 1.467 s → × 1.5
- $(1.22)(1.176)(1.5)(3.4 \times 10^{20}$ p/yr$) = 7.3 \times 10^{20}$ p/yr

Assume 90% → 6.5×10^{20} p/yr

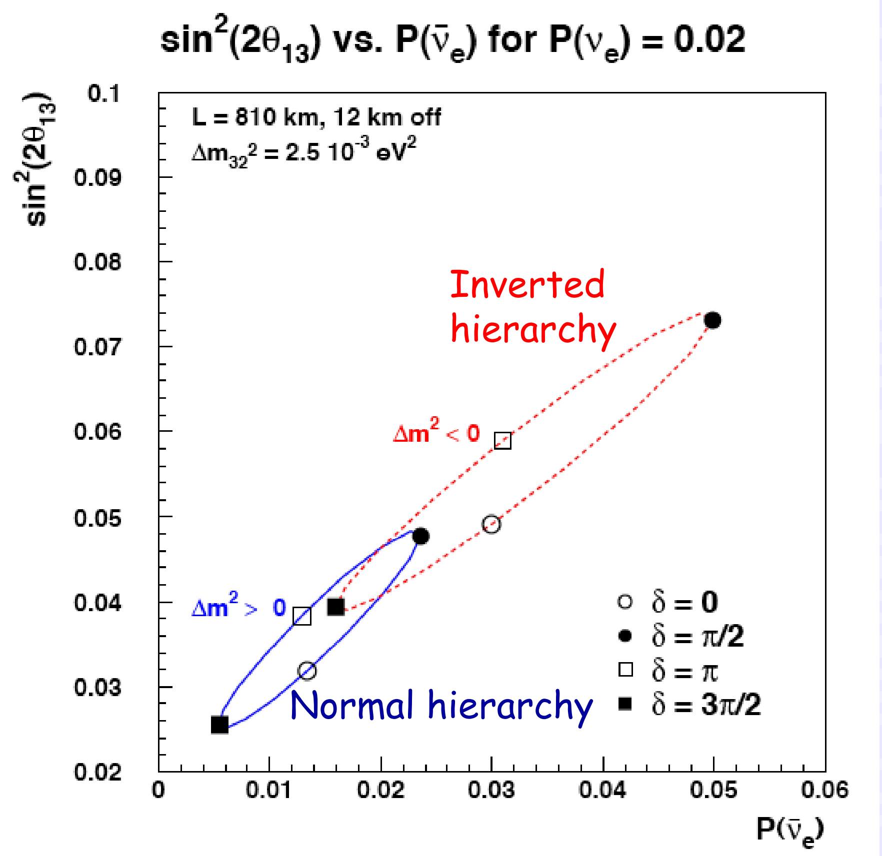
Statistically Limited

- NOνA will be statistically limited. Thus, the power of the experiment is proportional to mass times the neutrino flux.
- A Fermilab Proton Driver would provide 25×10^{20} pot/yr, a factor of x 4.
- Same effect as building 4 NOνA's which would cost $500M more and be truly enormous:



Interpreting what we measure

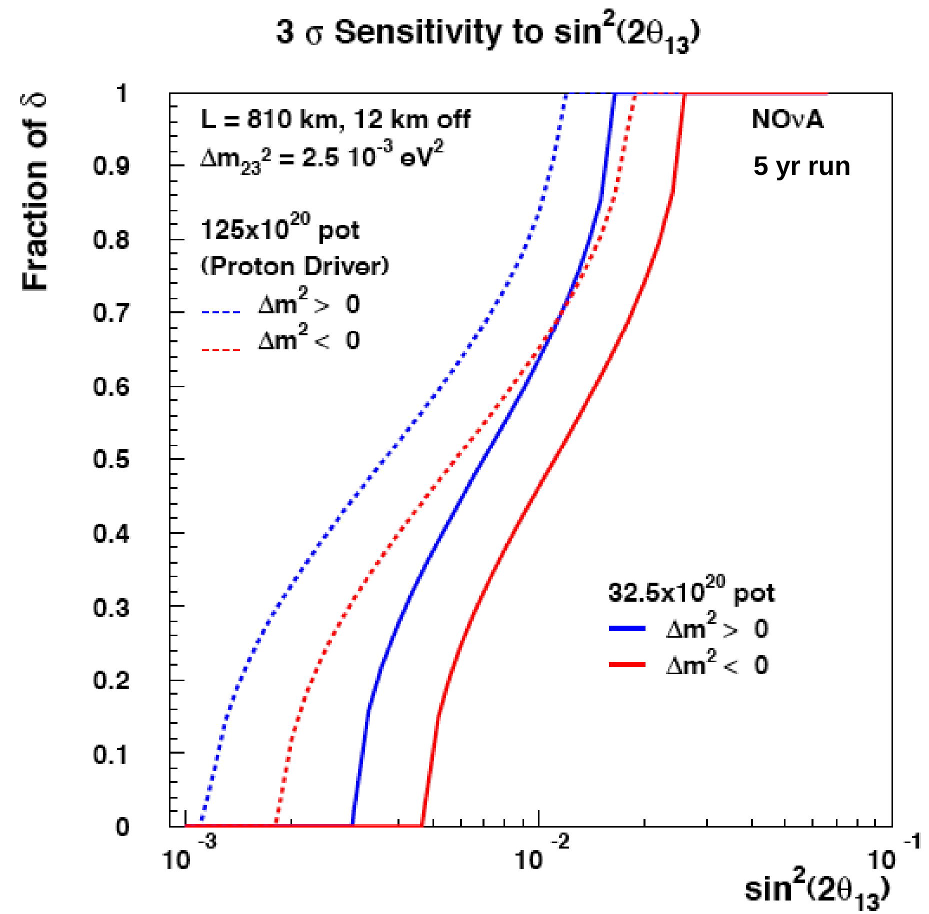
- Experiments measure oscillation probabilities
- Ambiguities in $\sin^2(2\theta_{13})$ due to CP phase δ and mass hierarchy
- Comparison of NOνA and T2K at different baselines can break ambiguities
- Possibly use a 2d NUMI off-axis detector at the 2d oscillation maximum
- Sensitivity varies with CP phase



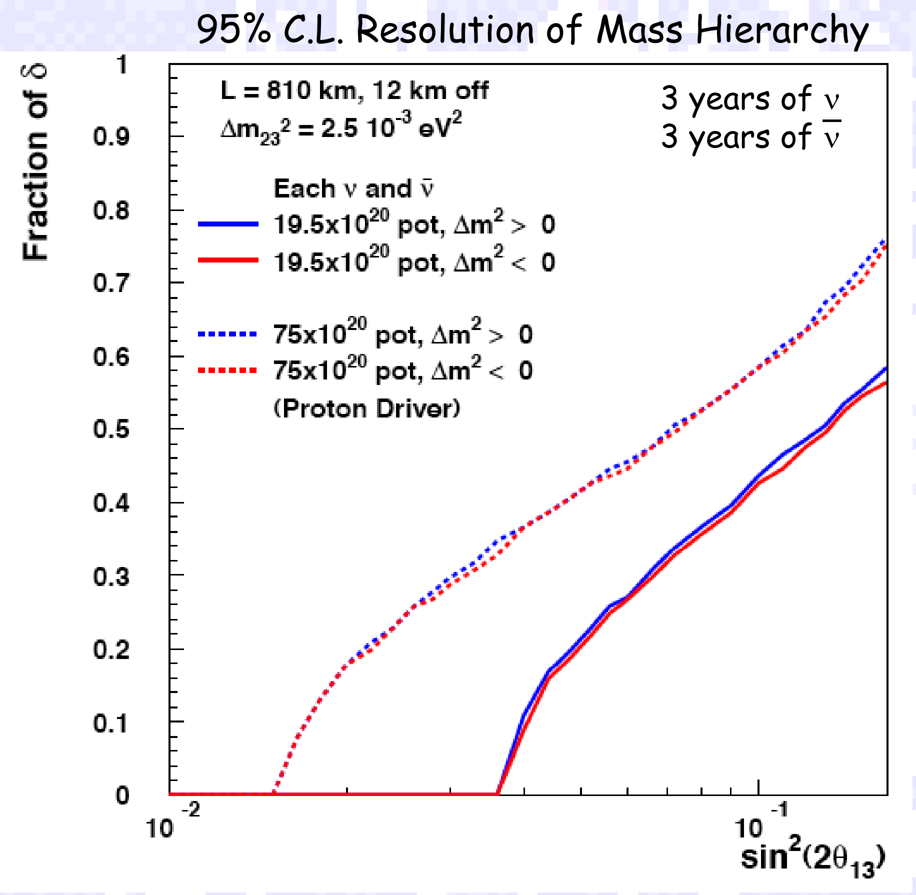
- Quote sensitivities vs the fraction of the CP ellipse covered

$\sin^2(2\theta_{13})$ Sensitivity

- Vertical axis is the fraction of possible δ values for which a 3σ discovery could be made.
- At large values of $\sin^2(2\theta_{13})$ a 3σ discovery can be made for all values of δ.
- At lower values of $\sin^2(2\theta_{13})$ a 3σ discovery is only possible for a range of δ.
- 5% systematic error on background determination included.



Resolving the Mass Hierarchy



There is a reasonable region of parameter space for which NOνA can resolve hierarchy. Proton Driver extends reach by factor of 2.

Resolving the Mass Hierarchy (cont.)

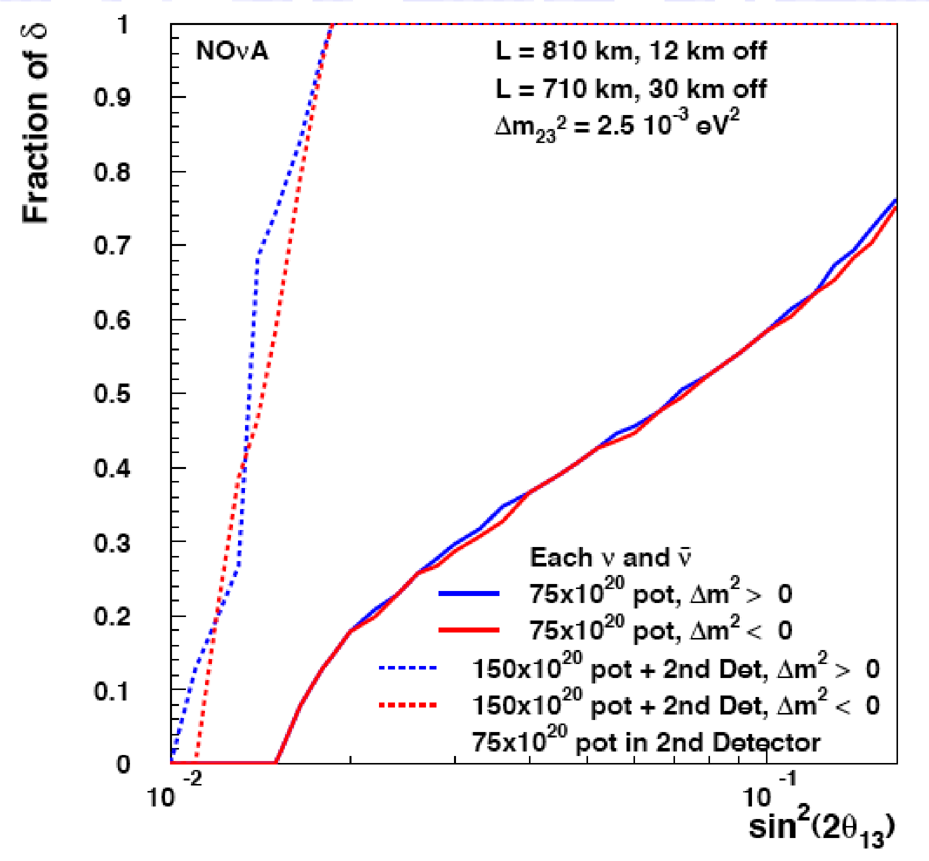
NOνA alone and with an additional off-axis detector at the 2d maximum

At 2d oscillation maximum

- L=710 km, 30 km off-axis
- Energy lower by x 3
  - ⇒ Matter effect smaller by x 3
  - ⇒ CP violation larger by x 3

Mass hierarchy resolved for all δ for $\sin^2(2\theta_{13}) > \sim 0.015$

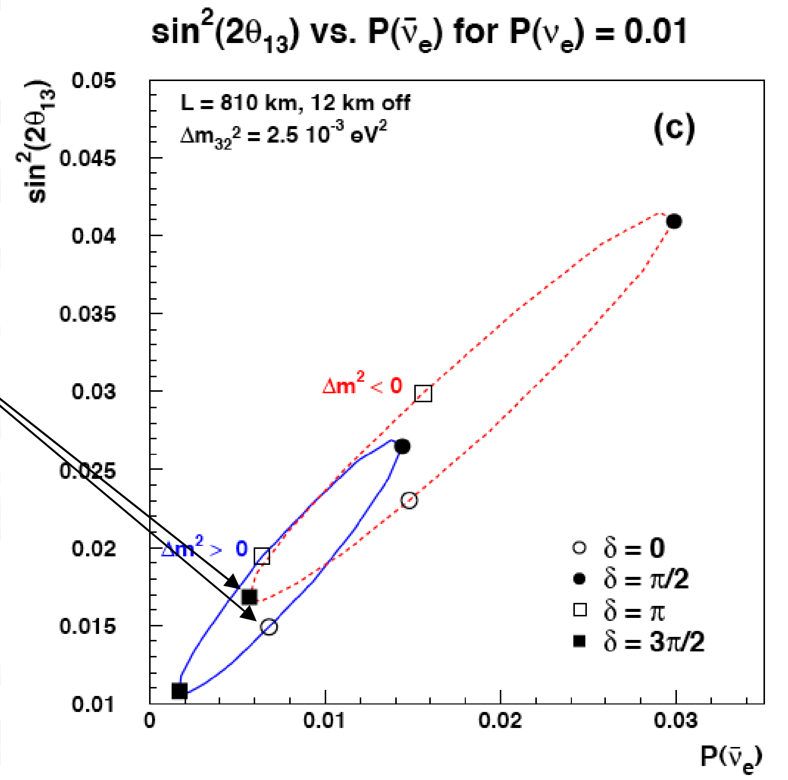
95% C.L. Resolution of Mass Hierarchy



12 years with proton driver
6 years with 2 detectors

Sensitivity to CP Violation

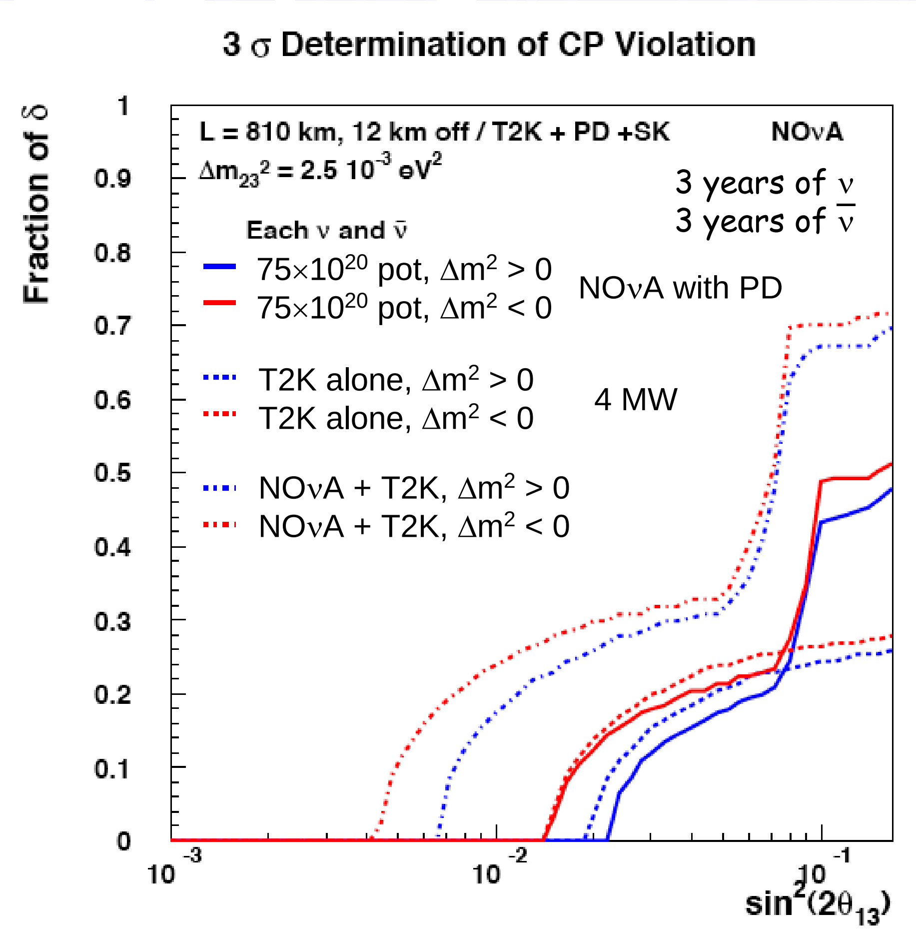
- Long baseline experiments generally need to know the hierarchy to measure the CP phase
- Maximal CPV for one mass ordering can have ν and $\bar{\nu}$ probabilities corresponding to no CPV for the other mass ordering



- Neither NOνA nor T2K can demonstrate CP violation in 6 years of running without enhanced proton sources

Sensitivity to CP Violation (cont.)

- Fraction of possible δ values for which there is a 3σ demonstration of CP violation
  - i.e. δ is neither 0 nor π for both mass orderings.

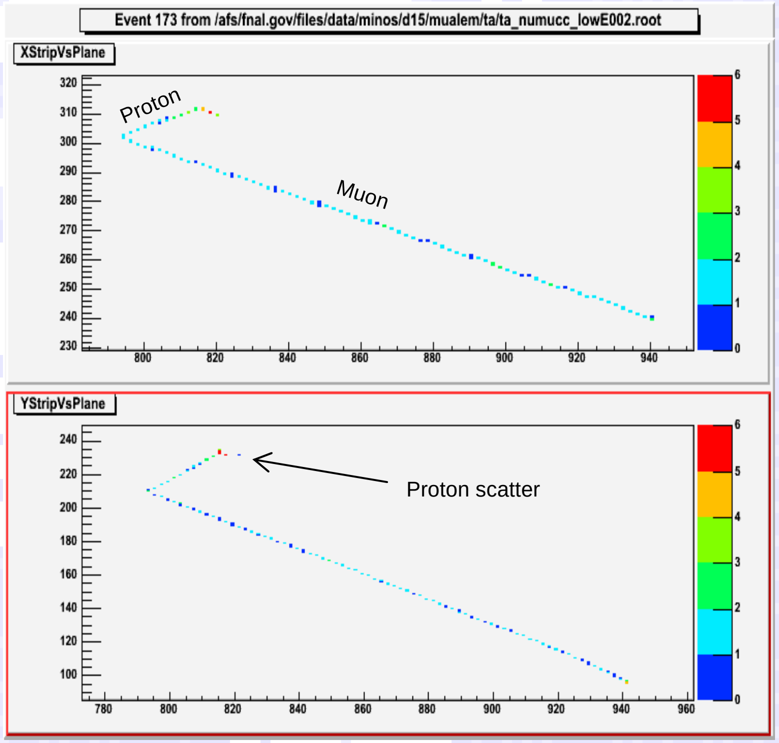


Precise Determination of $\sin^2(2\theta_{23})$

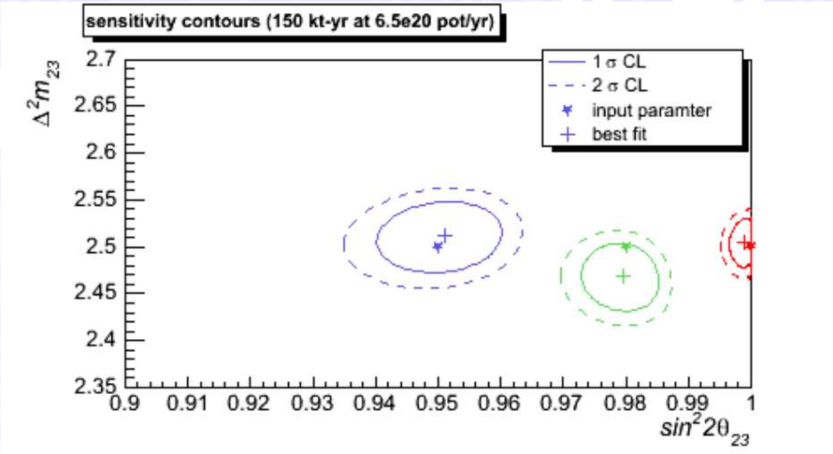
- Important because:
  - If mixing is maximal, could be due to unknown symmetry
  - $\nu_\mu \rightarrow \nu_e$ oscillation is proportional to $\sin^2(\theta_{23})\sin^2(2\theta_{13})$.
  - If mixing is not maximal, this leads to an ambiguity in comparing reactor and accelerator results.

- Precision measurement requires
  - good statistics
  - excellent ν energy resolution
  - good control of systematics

- Use totally contained quasi-elastic events
  - Very clean, essentially no NC background
  - Can measure $\sin^2(2\theta_{23})$ to ~ 1-2% level

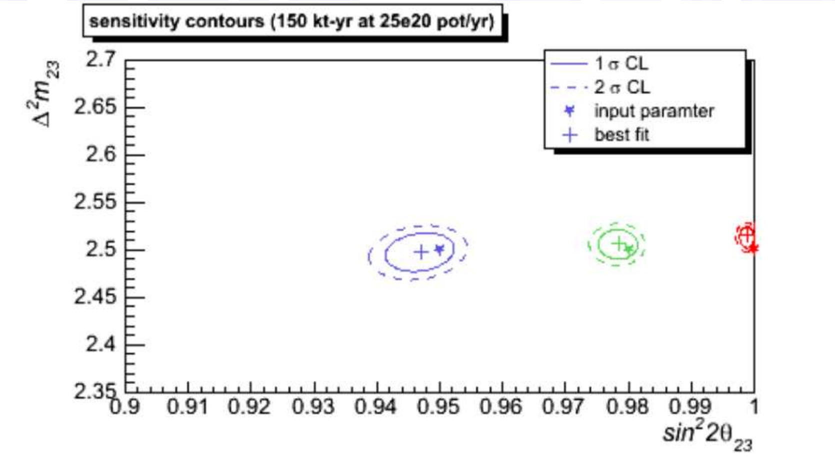


Precise Determination of $\sin^2(2\theta_{23})$



1σ and 2σ contours for simultaneous measurement of Δm^2_{32} and $\sin^2(2\theta_{23})$ for a 5 year ν run without a Proton Driver.

5 year ν run with Proton Driver



For maximal mixing, error on $\sin^2(2\theta_{23})$ is about 0.004 without Proton Driver and 0.002 with a Proton Driver.

Summary

- Fermilab's long-range plan includes an ongoing program of long baseline neutrino experiments.
- MINOS is the first step in this program and is just now underway (see talk by Mary Bashi at this workshop).
- NOνA would be the next step
  - Presented current design to Fermilab PAC yesterday
  - Hoping for rapid consideration, by June at the latest
  - NuSAG review by funding agencies to report in June
  - NOνA and Fermilab are very open to new collaborators
- A Proton Driver is being considered to augment the neutrino program and to support a wide range of other physics programs (see talk by John Ellis at this workshop)
- In some scenarios a 2^d NUMI off-axis detector at the 2^d maximum is helpful